Optical and VLF Imaging of Lightning-Ionosphere Interactions

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LONG-TERM GOALS

This work addresses one of the key topics of space physics research recommended for the next decade in the National Research Council 1995 report "A Science Strategy for Space Physics," namely, the middle and upper atmospheres and their coupling to regions above and below, specifically dealing with the electrodynamic coupling between the troposphere, mesosphere, and the lower ionosphere, driven by thunderstorm systems. Our long-term goal is to quantify the effects of lightning on the mesosphere/lower ionosphere, both on a regional and global scale.

OBJECTIVES

Objectives of the current three year effort are to address the following scientific questions: What is the extent and importance of ionospheric heating due to impulsive electromagnetic (EMP) and quasi-static (QE) fields released in lightning discharges which produce elves and sprites? What is nature and extent of the fine structure observed in sprites? Is the fine structure compatible with available theoretical models? Under what conditions does lightning-induced electron precipitation (LEP) represent a significant fraction of the overall particle loss rate from the radiation belts? What is the spatio-temporal structure of LEP regions? What is the geographic (longitude) and geomagnetic distribution of LEP event activity? What are the relative rates of occurrence of LEP events ducted, non-ducted and magnetospherically reflected whistlers? What are the lateral and altitude profiles of ionospheric disturbances registered as early/fast perturbations on subionospherically propagating VLF signals? Are some types of thunderstorms or lightning flashes more likely to produce these disturbances? What is the underlying physical mechanism of early/fast VLF events? How are they related to the optical phenomena of sprites and elves?

APPROACH

Our approach consists of the use of optical and wideband VLF measurements to document high altitude optical phenomena together with the causative lightning flashes and VLF holographic imaging of the ionospheric disturbances in the form of rapid changes in ionospheric conductivity. The conductivity changes are caused either *directly* as a result of heating of the ionosphere immediately above the discharges by EMP and QE fields or *indirectly* as a result of lightning-induced precipitation of bursts of energetic electrons from the radiation belts. The measurements are conducted with VLF receiver systems deployed at thirteen high schools spaced ~65 km apart, ranging from Cheyenne/Wyoming to Las Vegas/New Mexico, with the students and teachers at these schools involved in the program as part of our educational outreach efforts. Optical measurements consist of

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14. ABSTRACT
This work addresses one of the key topics of space physics research recommended for the next decade in the National Research Council 1995 report ???A Science Strategy for Space Physics,??? namely, the middle and upper atmospheres and their coupling to regions above and below, specifically dealing with the electrodynamic coupling between the troposphere, mesosphere, and the lower ionosphere, driven by thunderstorm systems. Our long-term goal is to quantify the effects of lightning on the mesosphere/lower ionosphere, both on a regional and global scale.

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telescopic imaging as well as photometric measurements using a novel photometric array (called the WASP) designed and built at Stanford. The key individuals involved are graduate student(s) that are either fully funded under this program or partly funded by an associated NSF grant, ~10% effort of an engineer, and the Principal Investigator. The students are involved in all aspects of the program, including construction of equipment and software, deployment, data acquisition and interpretation, as well as educational outreach (for example by providing lectures at the high schools). The engineer oversees design and construction of circuit cards for the receiver(s) and also sometimes leads the initial installations at remote sites.

WORK COMPLETED

During the past year, holographic VLF data was acquired at eleven HAIL (holographic array for ionospheric lightning) sites in a nearly continuous manner. In addition, two new sites have been established, at Fountain and Rye, Colorado, establishing a denser array (~30 km spacing) of nine sites in the middle of the overall HAIL array. Measurements with this new system are ongoing, with the first results having been presented at the Fall 2001 AGU meeting and the GEM and CEDAR conferences in June 2002. The increase in resolution achieved by the denser array has facilitated definitive determination of Early/Fast VLF events measured on the HAIL array as being caused by sprite halo events, as reported in [*Moore et al*., 2002]. With the advent of GPS timing, and the availability of simultaneous broadband recordings at all sites, it has been possible, for the first time, to measure the coherent phase differences between the multiple sites. This new coherent measurement has led to a brand new method of highly sensitive determination of the lower ionospheric electron density profile and the identification of the properties of individual waveguide modes which constitute the total VLF signal observed at the HAIL sites [*Bainbridge and Inan*, 2002]. Another new discovery during the past year has been the first ever measurement of energetic electron precipitation induced by magnetospherically reflected whistlers [*Inan et al.*, 2002]. These types of whistlers persist for up to 10-20 seconds following the causative lightning strike, reflecting and propagating back-and-forth between hemispheres. In HAIL VLF data, these events were identified as relatively large signal amplitude/phase changes which occur with onset delays of >3 seconds with respect to the causative strike and which exhibit unusually long onset durations of >5 seconds. This new finding indicates that lightning-generated whistlers may play a much larger role in the loss of radiation belt electrons, since waves injected by each lightning flash apparently continue to precipitate for many (up to 10-20) seconds.

In terms of optical measurements, work was concentrated on the publishing of the second and third papers reporting the results of our telescopic imaging and photometric measurements of sprites [*Gerken and Inan*, 2002]. The contents of these papers constitute the bulk of the PhD work of Ms. Elizabeth Gerken, who is expected to graduate within the upcoming school year (about April 2003). In addition, two optical campaigns were conducted in South Africa (in coordination with our colleagues from Denmark who conducted measurements in Europe) in the summer of 2001 and in Japan in the winter of 2002 (in collaboration with our colleagues from Japan and Australia who conducted measurements at both ends of the geomagnetic field line) to measure geomagnetically conjugate effects of strong lightning storms. The fact that upward-driven energetic electron beams produced in the hemisphere of the parent lightning flash would produce detectable optical emissions in the conjugate region were predicted in the context of the PhD work of Nikolai Lehtinen [*Lehtinen et al.*, 2001].

RESULTS

The so called Early/Fast VLF events, involving perturbations in amplitude and phase of VLF signals observed at the HAIL array have been shown to be consistent with that which would be produced via scattering from electron density disturbances associated with sprite halo events. This finding identifies the sprite-halo, which was discovered in the course of our work under this grant [*Barrington-Leigh and Inan*, 2001].

A methodology for determining the mode structure of a VLF signal propagating in the earth-ionosphere waveguide has been formulated, which can be used to determine the electron density profiles in effect in the nighttime D-region.

A statistical study of the occurrence of lightning induced electron precipitation events (LEP events) showed the prevalence of non-ducted whistler induced precipitation events over ducted whistler induced events detectable on the HAIL array.

The first observation of LEP events induced by a magnetospherically-reflected whistler waves have been realized, suggesting a much larger potential role of lightning discharges in the loss of radiation belt particles.

Telescopic measurements of sprite structure have revealed a wide variety of shapes, sizes, and time scales, but careful analyses indicate that certain structures such as beading, faint downward branching, propagating diffuse glows, and columns appear repeatedly. Clear examples have been identified of the following observations of decameter-scale streamer and diffuse glow formations:

- Propagating diffuse glows are observed to move slowly and are broader than predicted for streamer formation.

- While many streamers move at velocities greater than the time resolution of regular video rate imaging, some have been found to move as slowly as 10^4 m/s.

- Sudden brightening of slowly-developing negative streamers may be indicative of a return stroke process in which the streamers connect with charge in a lowered ionosphere.

- Fine beading exists in many negative streamers and may possibly be a result of meteoric dust particles in the upper atmosphere.

- Columniform sprites may originate from positive branching streamers.

- Beads at the base of columns can glow for over 100 ms while slowly drifting upward (~10^4 m/s).

- Faint positive streamers are observed at the base of large bright sprite events.

- Some sprites having branching positive streamers and non-branching negative streamers may be double-headed streamers initiated from plasma enhancements such as vaporized meteoric dust.

- A transition region between streamer formation and diffuse glow is observed at ~80 km altitude.

- No structure is observed in telescopic images of the diffuse glow region, or “sprite halo.”

IMPACT/APPLICATIONS

The general impact of our results is the quantification of the contribution to ionospheric variability (especially the mesosphere and the D region) of lightning discharges. This contribution may be globally important, in view of the ~2000 thunderstorms active around the globe at any given time, maintaining a global lightning rate of ~100 flashes per second.

TRANSITIONS

The various Java-based and MATLAB-based analysis software developed by Stanford for the HAIL research project are being used by interested high school students at the schools that house our equipment. The recent improvement of our web server software has enabled students to manipulate and analyze data with capabilities similar to ours at Stanford. Our data is now easily accessible at http://www-star.stanford.edu/~hail/, which gives us the capability of expanding this educational outreach component to other schools.

RELATED PROJECTS

The Atmospheric Sciences Division of NSF jointly funds the holographic VLF measurements component of our project. Other related projects include broadband VLF observations carried out at Palmer Station, Antarctica, which allows us the opportunity to observe lightning-generated whistler waves, often associated with electron precipitation events detected by the HAIL system.

PUBLICATIONS

Journal Publications:

Pasko, V.P., U.S. Inan, and T.F. Bell, Mesospheric-tropospheric coupling due to sprites, *Geophys. Res. Lett., 28*, 3821-3824, 2001.

Lehtinen, N.G., U.S. Inan, and T.F. Bell, Effects of thunderstorm-driven runaway electrons in the conjugate hemisphere: purple sprites, ionization enhancements, and gamma rays, *J. Geophys. Res., 106*, A12, 28, 841, 2001.

Gerken, E.A. and U.S. Inan, Observations of decameter-scale morphologies in sprites (in press), *J. Atmos. Terr. Phys.*, 2002.

Gerken, E.A. and U.S. Inan, A survey of streamer and diffuse glow dynamics observed in sprites using telescopic imagery (in press), *J. Geophys. Res.*, 2002.

Mende, S.B., H.U. Frey, R.L. Rairden, H.T. Su, R.R. Hsu, T.H. Allen, T. Neubert and E.A. Gerken, Fine structure of sprites and the proposed global observation, *Cospar Colloquia Series Volume 12: Space Weather Study Using Multipoint Techniques,* edited by L.H. Liu, 2002.

Pasko, V.P., M.A. Stanley, J.D. Mathews, U.S. Inan, and T.G. Wood, Electrical discharge from a thundercloud top to the lower ionosphere, Nature, 416, 152, 2002.

Bainbridge, G. and U.S. Inan, Ionospheric D-region electron density profiles derived from the measured interference pattern of VLF waveguide modes (in review), *Radio Science*, 2002.

Robert C. Moore, C.P. Barrington-Leigh, U.S. Inan, and T.F. Bell, Early/fast VLF Events Produced by Electron Density Changes Associated with Sprite Halos (in review), *J. Geophys. Res.*, 2002.

Papers Presented at Scientific Conferences:

Pasko, V.P. and U.S. Inan, Multidimensional modeling of sprites, presented at the URSI United States National Radio Science Meeting, Boulder CO, January 4-8, 2001.

Gerken, E.A. and U.S. Inan, Telescopic imaging of sprites during summer 2000 campaign, presented at the United States National Radio Science Meeting, Boulder CO, January 4-8, 2001.

Inan, U.S., G.J. Fishman, J.B. Blake, H.J. Christian, and J. Bortnik, Terrestrial gamma ray flashes and energetic electron precipitation produced by a cyclonic thunderstorm in central Australia, presented at the United States National Radio Science Meeting, Boulder CO, January 9-12, 2002.

Neubert, T., T.H. Allen, R. Rairden, U. Inan, G. Bainbridge, A. Hughes, T. Modise, Results from the first conjugate sprites campaign, presented at the Fall Meeting of the American Geophysical Union, December 2001.

Gerken, E.A. and U.S. Inan, Characterization of fine structure in sprites, presented at the Fall Meeting of the American Geophysical Union, December 2001.

Gerken, E.A. and U.S. Inan, Telescopic imaging of sprites, invited talk presented at the 2001 Asia-Pacific Radio Science Conference, Tokyo, August, 1-4 2001.

Inan, U.S., Early/fast disturbances of the lower ionosphere, invited talk presented at the United States National Radio Science Meeting, Boulder CO, January 4-8, 2001.

Moore, R.C., C.P. Barrington-Leigh, and U.S. Inan, Early/fast disturbances of the lower ionosphere, presented at the United States National Radio Science Meeting, Boulder CO, January 9-12, 2002.

Peter, W. and G. Bainbridge, A study of the nighttime variation in mode structure of VLF signal propagation in the earth-ionosphere waveguide, presented the CEDAR Workshop, June 2002.

Peter, W. and U.S. Inan, A Statistical Examination of the Occurrence of Lightning Induced Electron Precipitation Caused by Whistler-Induced Scattering and Its Effect On VLF Earth-Ionosphere Waveguide Propagation, presented at the GEM Workshop, June 2002.